Journal of Arid Environments (1994) 28: 265–279

The relationship of precipitation seasonality to the flora and stable isotope chemistry of soils in the Vizcaíno desert, Baja California, México

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(*Received 7 June 1993, accepted 10 June 1993*)

The proportion of winter to summer rainfall decreases with decreasing latitude in the Vizcaíno desert of Baja California, Mexico. Vegetation characteristics, soil carbon contents, the stable carbon isotope composition of soil organic matter and pedogenic carbonate, and the stable oxygen isotope composition of carbonate were measured at four locations along this precipitation transect. The number of species (~ 20), the ground cover (~ 30%), and the proportion of succulents to total species (~ 60%) were similar at all sites. The northernmost site possessed species (e.g. *Ephedra californica*, *Yucca schidigera*) peculiar to winter rainfall zones while the southern site had several species typically common only to summer rainfall zones (e.g. *Cercidium praecox*, *Lemaiveocereus thurberi*). Organic carbon contents of the soils were low and varied little with rainfall distribution. $\delta^{13}C$ values of organic carbon were approximately 2 to 3‰ more positive at the southernmost site than at the other locations, possibly reflecting a greater proportion of biomass from either succulents or C_4 summer grasses. The $\delta^{13}C$ value of tissue from a representative CAM plant (*Opuntia echinocarpa*) did not vary with precipitation patterns suggesting that the $\delta^{13}C$ values of CAM species are insensitive to the climate variations in this area. $\delta^{13}C$ values of pedogenic carbonate varied little with location (−4·1 to −5·8‰), reflecting small differences in soil respiration rates with latitude. $\delta^{18}O$ values of pedogenic carbonate varied significantly from north (−3·6‰) to south (−7·3‰), and are interpreted as reflecting the differences in the relative contribution of isotopically 'heavy' winter storms from the Pacific to the isotopically 'light' summer and fall storms from the southern Pacific and the Gulf of Mexico. The results of the study reinforce the observation that subtle climatic differences in arid regions are reflected in the floral composition and in the chemistry of the soils. The Holocene

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data obtained in this study provide a basis for interpreting the climatic significance of isotopic data from paleosols in the Vizcaíno Desert region.

Keywords: desert soils; soil carbon; stable isotopes; precipitation seasonality; species distribution; Baja California peninsula

Introduction

The Baja California, Mexico peninsula is a narrow segment of land that extends nearly 1400 km in a north-west to south-easterly direction (Fig. 1). With the exception of its elevated mountainous ridges, the climate of the peninsula is among the most arid in North America (Hastings & Turner, 1965). Within this arid region, vegetational communities vary in response to subtle climatic variations. The largest of these desert floral provinces is the Vizcaíno Desert, which extends from El Rosario in the north to beyond San Ignacio in the south (Fig. 1).

The unique flora of the Vizcaíno desert is derived from various regions, some being related to the Californian region to the north, the Sonoran-Chihuahuan Desert to the north and east, and from the subtropics of Mexico and Central America (Wiggins, 1960). Among the more unusual and visually striking species include the boojum tree (*Fouquieria columnaris*), elephant tree (*Pachycormus discolor*), and carbon (*Packycereus pringlei*).

Despite its general floral homogeneity, the Vizcaino desert has a distinct climatic gradient, with a decreasing winter rainfall component, and an increasing summer contribution, from north to south. Recognizing this climate gradient, we chose to investigate the effect of seasonality of rainfall on species distribution, the stable isotope chemistry of the soils, and soil morphology. This paper presents the results of our investigation of these relationships and their importance to issues of paleoenvironmental reconstruction in the region.

Materials and methods

Study area

Four study sites were selected along a north-west to south-east transect of the Vizcaíno desert, approximately along the central axis of the peninsula (Fig. 1). Study sites were selected on stable Holocene stream terraces. Stream geomorphology was similar to that described by McAuliffe (1991). Three distinct Holocene geomorphic surfaces were present at each site, from lowest to highest: (1) an active stream wash, (2) a gravelly, partially vegetated bar deposit, and (3) a stable terrace, elevated 1 to 2 m above the active wash. The terrace typically consisted of approximately 50 cm of gravel-poor alluvium over a gravel-rich alluvium, and showed no evidence of recent flooding or stream modification. Sites on these terraces were chosen for intensive soil and vegetative study, because we anticipated that their properties reflected responses to regional precipitation rather than to floodwaters (McAuliffe, 1991).

Vegetation

At each site, ground covered by perennial species was measured in six 15-m transects. The point of origin and direction of transects was random, but they were all located on the same terrace and within ~ 50 m of the site selected for soil studies. To determine species density, individual plants were counted within 1 m of each transect, thus converting the transects into 30 m^2 quadrats.

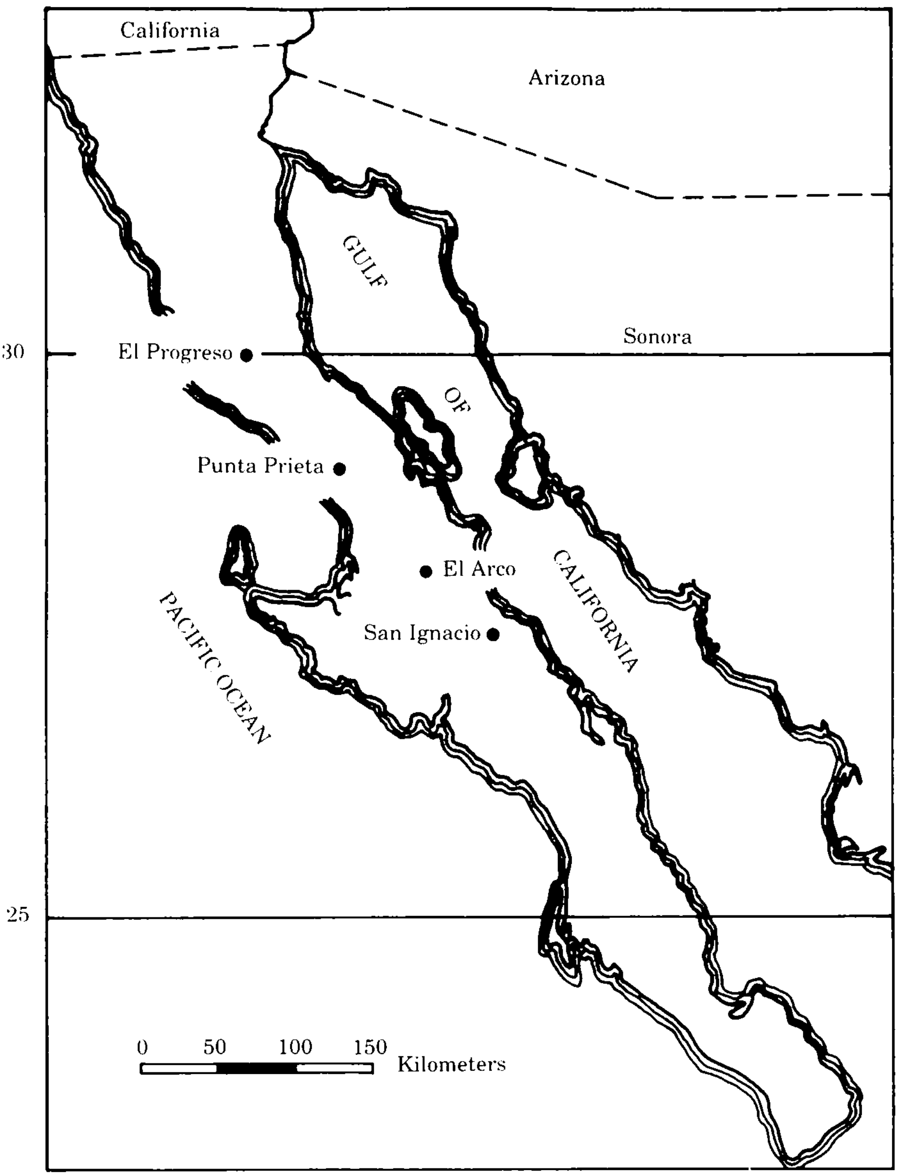

Figure 1. Location of study sites in the Baja California peninsula.

Soils

Pedogenic carbonate accumulated predominantly on gravels within the soils. It was observed that the location of carbonate deposition was (1) entirely on gravel tops and sides in the two southernmost sites and (2) entirely on gravel bottoms and sides in the northernmost sites. This difference in the location of carbonate deposition is believed to reflect differences in soil thermal gradients that affect soil water movement in winter *vs.* summer rainfall regimes (Amundson *et al.*, 1992). Additionally, carbonate is located on gravels almost at the soil surface at the northern sites while it was found only at depths of

50 cm or greater in the southern sites. This suggests differences in the effectiveness of precipitation between the sites, with the southern sites receiving rainfall in more concentrated pulses capable of leaching carbonate to greater depths than in the northern locations.

Soil profiles were exposed at each site through hand excavation. Morphological descriptions were made in the field using standard procedures (Soil Survey Staff, 1981). Samples for laboratory analyses were collected in two ways. Bulk samples for isotopic analyses of organic matter were collected by soil horizon. Samples for isotopic analyses of pedogenic carbonate were collected by 20 cm intervals from the uppermost point where pedogenic carbonate was visible on gravels. Within each interval, gravels possessing visible pedogenic carbonate coatings were separated from the profile and stored for later laboratory preparation.

Isotopic analysis

In the laboratory, clasts containing pedogenic carbonate coatings were rinsed, and lightly brushed, under distilled water to remove any adhering, non-pedogenic carbonate. Coatings were then chipped off the gravels with file, ground to a fine powder in a mortar and pestle, and placed in glass vials. Subsamples were roasted under vacuum at 425°C for 4 h to pyrolyse co-existing organic matter. The baked samples were then reacted with 100% H_3 PO_4 and the released CO_2 was purified cryogenically (McCrea, 1950) and measured by manometry. The $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios were determined by mass spectrometry.

Samples of soil horizons were passed through a 2 mm sieve. Subsamples of the sieved soil were ground to a fine powder in a mortar and pestle, acidified in 6 N HCl to remove co-existing carbonate, rinsed in deionized H_2O, and dried through lyphilization. Cellulose of selected CAM plants was extracted using the methods of Sternberg (1989), while whole samples of the same plants were acidified in 1 N HCl, rinsed, and lyphilized. The pretreated soil and plant samples were combusted in sealed tubes containing Cu, CuO, and Ag (Minagawa *et al.*, 1984). The released CO_2 was purified cryogenically, its yield measured manometrically, and its $^{13}C/^{12}C$ ratio measured by mass spectrometry.

All isotope ratios are expressed in the δ notation where:

$$\delta{*}X = ((*X/X)_{sample}/(*X/X)_{std} - 1) \times 1000$$

For carbon, $*X/X$ is $^{13}C/^{12}C$ and the standard is the PDB carbonate. For oxygen, $*X/X$ is $^{18}O/^{16}O$ and the standard is PDB carbonate for carbonate samples and standard mean ocean water (SMOW) for water samples. Precisions of determinations (assessed from replicate analyses of the same soil samples) were ±0·50‰ for carbon in carbonate, ±0·20‰ for oxygen in carbonate, ±0·20‰ for carbon in organic matter.

Climate of the Vizcaíno Desert

Monthly temperatures for the four study sites are illustrated in Fig. 2(a). All four sites display similar monthly variations and annual means (18·6°, 19·5°, 20·5°, and 19·4°C from north to south, respectively). Differences in temperatures between sites during the fall, winter, and spring probably reflect slight differences in oceanic influence and elevation.

By far the greatest differences among the sites, in terms of climate, is in rainfall distribution (Fig. 2(b)). The Baja California peninsula receives its precipitation from a combination of four sources (Hastings & Turner, 1965): (1) winter Pacific cyclonic storms, (2) summer monsoonal storms (primarily in July), (3) fall storms from Pacific tropical cyclones (primarily in September) and (4) moisture-laden easterlies from the Gulf of Mexico. The importance of these different sources varies with location, but 'the peninsula falls consistently under the dominance of none of these regimes and fitfully

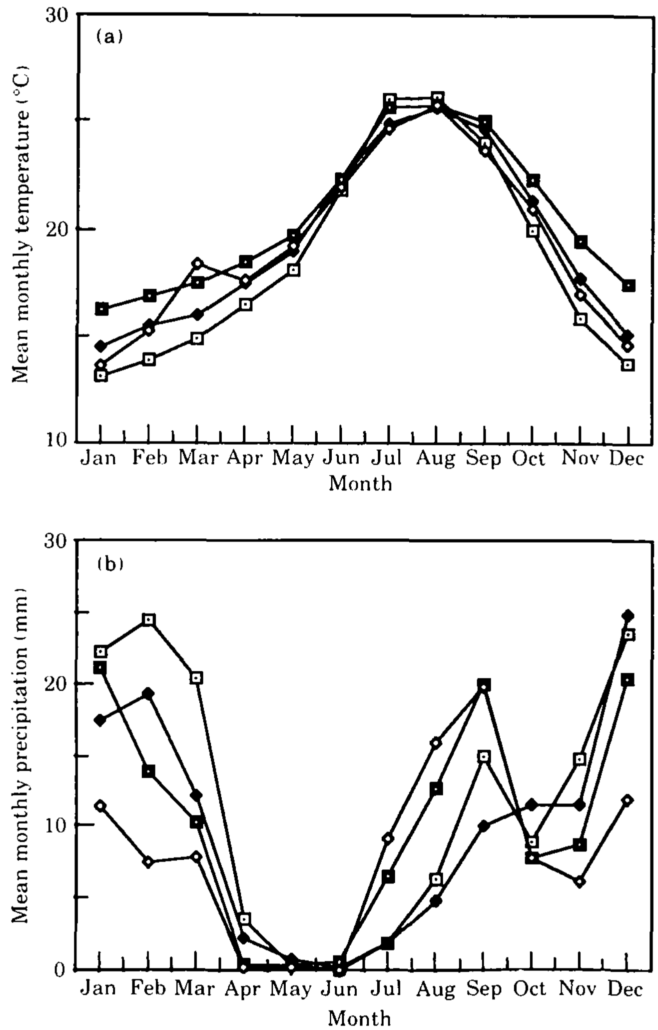

Figure 2. Monthly variation in (a) temperature and (b) precipitation at the study sites. Data from CICESE (1990). (-□-, El Progreso; -◆-, Punta Priela; -■-, El Arco; -◇-, San Ignacio).

under the influence of all four' (Hastings & Turner, 1965), explaining the extreme aridity of the region, and the unpredictability of precipitation.

Differences in the relative importance of these precipitation sources are evident in the rainfall data of the study sites. All four sites share a common characteristic of low to non-existant spring rain following a major winter precipitation pulse. However, the amount of the winter precipitation decreases steadily from north to south (Fig. 2(b)). In addition, a distinct summer precipitation pulse increases along this same north to south transect. The greatest amount of this summer precipitation falls in the month of September, corresponding to either the influence of tropical cyclones or easterly winds. Significant rains also fall in the southern sites during July and August, possibly reflecting the influence of summer monsoons.

Total precipitation decreases from north to south (141 mm in El Progresso to 97 mm in San Ignacio) (Table 1). The proportion of winter to total precipitation decreases along this transect (48% to 27%) while the relative summer precipitation increases (16% to 46%).

Table 1. *Rainfall distribution of the study sites (data from CICESE, 1990)*

Site	Latitude	MAP (mm)	% MAP* Winter	Spring	Summer	Fall
El Progreso	30°N	141	48	3	16	33
Punta Prieta	29°N	115	42	2	14	42
El Arco	28°N	122	37	1	32	30
San Ignacio	27·50°N	97	27	1	46	26

* The seasons represent consecutive 3-month segments of a calendar year.

Results and discussion

Plant distribution

The results of the plant inventories are given in Table 2. The four sites have several features in common: (1) species richness (18 to 20 species/site), (2) proportion of succulents to total species (0·56 to 0·65), and (3) proportion of ground cover (0·26 to 0·40). These similarities are expected given that all the sites are well within the recognized Vizcaíno floral province (Wiggins, 1960).

When individual species are considered, however, subtle distinctions emerge that correlate with precipitation seasonality (Table 2). Several species that occur only at the northernmost site are typical of winter rainfall regions in the United States (i.e. *Ephedra californica*, *Yucca schidigera*) while several species at the southernmost site are typical of summer precipitation deserts (*Cercidium praecox*, *Lemaineocereus thurberi*). Table 2 illustrates that while all sites contain a set of common species, there is a systematic shift in perennial species from north to south. As part of this shift, summer C_4 grasses (*Bouteloua barbata*, *Muhlenbergia microsperma*) were found only at the southernmost site. Below we discuss the effect that these floral patterns have on the carbon isotope chemistry of the soils.

Stable isotope chemistry of soils

The organic carbon content was low (<1%) in all soils (Table 3), and decreased with increasing depth. The southernmost site had slightly greater carbon contents, possibly due to lower gravel contents (data not shown). Assuming a soil bulk density of 1·4 g cm^{-3}, and subtracting gravels > 25 mm in diameter from the soil volume, the total organic carbon in the upper 50 cm of the soils was approximately 950, 680, 710, and 2,660 g m^{-2} from north to south, respectively. The error in these values is probably ± 50% because of uncertainties in the true soil bulk densities and because of errors in estimating gravel contents in the field.

The $\delta^{13}C$ value of soil organic matter reflects the relatively long-term isotopic composition of the standing biomass. C_3 plants have ^{13}C values which vary around a mean of about − 27‰ (Deines, 1980). Nearly all the non-succulent species at the different sites were composed of C_3 species (we were unable to identify positively the photosynthetic pathway of only five species). C_4 plants, of which only grasses were members of in this study, have $\delta^{13}C$ values which vary around a mean of −12‰ (Deines, 1980). CAM plants, which made up about 50% of the perennial species in this study, have $\delta^{13}C$ values which can vary between C_3 and C_4 plants, depending on environmental conditions (Osmond *et al.*, 1973). As discussed below, the measured $\delta^{13}C$ values of CAM species in this study were around −13‰.

Table 2. *Density, richness, and ground cover of plant species at the study sites*

Species	Species density*			
	El Progreso	Punta Prieta	El Arco	San Ignacio
Ambrosia chenopodifolia	0·006 ± 0·006			
Ephedra sp. (*californica* ?)	0·011 ± 0·011			
*Yucca schidigera***	P†			
*Agave cerulata***		P		
Atriplex sp.	0·094 ± 0·016	0·033 ± 0·022		
*Ferocactus gracilis***	0·011 ± 0·007	0·006 ± 0·006		
*Fouquieria columnaris***	P	0·011 ± 0·007		
*Opuntia molesta***	P	P		
*Pachycormus discolor***		P		
Viscainoa geniculata		0·022 ± 0·011		
Acacia gregii	P	P		P
Ambrosia pumila		0·011 ± 0·011	0·055 ± 0·036	
Cercidium microphyllum	P			P
*Echinocereus engelmanni***	0·006 ± 0·006			0·006 ± 0·006
*Fouquieria diguetii***		0·006 ± 0·006	0·011 ± 0·007	
Larrea tridentata	0·044 ± 0·020	0·017 ± 0·007	0.022 ± 0·011	0·033 ± 0·012
*Lophocereus schottii***	0·006 ± 0·006	0·006 ± 0·006	P	0·028 ± 0·016
Lycium sp.	0·122 ± 0·051	P	0.022 ± 0·011	
*Machaerocereus gummosus***		0·006 ± 0·006	0.083 ± 0·035	P
Mammillaria sp.	P	0·006 ± 0·006		P
*Opuntia cholla***		0·161 ± 0·054	0.056 ± 0·019	0·956 ± 0·118
*Opuntia echinocarpa***	0·006 ± 0·006	0.067 ± 0·038	P	0·017 ± 0·011
*Opuntia tesajo***	0·022 ± 0·011			P
*Pachycereus pringlei***	P	P	P	0·011 ± 0·007
*Pedilanthus macrocarpus***		0·044 ± 0·019	0.011 ± 0·007	P
Prosopis glandulosa		P	P	0·039 ± 0·016
Simmondsia chinensis	P		P	
*Yucca valida***		P	0.006 ± 0·006	
*Agave deserti***			0·050 ± 0·050	
*Bursera hindsiana***			P	
*Bursera microphylla***			0·011 ± 0·007	
Encelia sp. (*californica* ?)			0·128 ± 0·096	
Euphorbia misera			0·011 ± 0·011	
Euphorbia xantii			0·006 ± 0·006	
*Jatropha cinerea***			0·039 ± 0·020	0·022 ± 0·011
Asclepias subulata				0·083 ± 0·077
Cercidium praecox				P
Grasses‡				1·167 ± 0·209
*Lemairocereus thurberi***				P
Stephanomaria sp.				0·006 ± 0·006
Species richness§	18	20	20	18
Proportion of succulents‖	0·56	0·65	0·60	0·61
Ground cover¶	0·31 ± 0·05	0·28 ± 0·09	0·26 ± 0·04	0·40 ± 0·07

* Average number of individuals m^{-2} ± S.E.M. in 30 m^2 quadrats, $n = 6$.
† P denotes species present at site (within ~50 m of soil site), but not encountered within quadrats.
‡ *Bouteloua barbata* and *Muhlenbergia microsperma* mostly under *O. cholla*.
§ Total number of perennial species at site.
‖ Total number of succulent species richness.
¶ Average ground cover of perennial species ± standard error of the mean, 15 m transects, $n = 6$.
** Succulent species.

Table 3. *The quantity and isotopic composition of soil organic C at the study site*

Site	Soil depth (cm)	Organic C (%)	$\delta^{13}C$ (‰)	Mean $\delta^{13}C$* (‰)
El Progreso	0–2	0·29	−24·3	−23·3
	2–6	0·23	−23·6	
	6–39	0·17	−23·4	
	39–66	0·16	−22·9	
	66–86	0·16	−23·3	
	86–120	0·10	−23·8	
	120–140	0·09	−26·1	
Punta Prieta	0–3	0·36	−21·4	−21·7
	3–6	0·25	−18·7	
	6–14	nd†	nd	
	14–32	0·10	−21·7	
	32–62	0·04	−23·0	
	62–93	nd	nd	
	93–101	0·07	−25·9	
	101–145	0·03	−27·5	
El Arco	0–1	0·30	−21·9	−21·8
	1–7	0·34	−19·2	
	7–32	0·14	−22·4	
	32–49	0·17	−21·8	
	49–65	0·12	−22·9	
	65–73	0·11	−22·3	
	73–86	0·06	−23·0	
	86–96	0·05	−23·8	
San Ignacio	0–3	0·71	−20·4	−20·2
	3–8	1·07	nd	
	8–14	0·48	−20·1	
	14–19	0·43	−20·4	
	19–25	0·37	−20·4	
	25–35	0·20	−20·2	
	35–53	0·15	−19·9	
	53–67	0·06	−22·2	
	67–98	0·05	−22·8	
	98–148	0·05	−24·6	

* Weighted mean for entire profile calculated using a bulk density of 1·4 g cm^{-3} and subtracting soil volume occupied by gravel.
† Not determined.

The $\delta^{13}C$ of the soil organic matter increases from a weighted mean (based on mass of organic carbon/horizon) of −23·3‰ in the north to −20·2‰ in the south (Table 3). Assuming δ^{13} values of C_3 and CAM plants to be −27‰ and −13‰, respectively, the measured $\delta^{13}C$ values of the soil organic matter can be interpreted as reflecting a decrease in the C_3 plant contribution to soil organic matter from the northern (~74% C_3) to southern (~51% C_3) sites. The most plausible explanation for this trend is that CAM plants constitute a greater percentage of the biomass (even though they do not vary in total species percentage) with increasing summer precipitation. Another reason for the trend in the $\delta^{13}C$ value of soil organic matter with latitude may be the presence of C_4 grasses at the southernmost site (Table 2). However, we also investigated the possibility that the $\delta^{13}C$

value of CAM plants, and the soil organic matter derived from them, might vary with latitude in response to precipitation patterns (Osmond *et al.*, 1973). Cellulose prepared from a species common to all sites, *Opuntia echinocarpa*, showed no consistent isotopic variation with latitude ($\delta^{13}C = -11{\cdot}5$, $-10{\cdot}1$, $-8{\cdot}9$, and $-10{\cdot}4$‰ from north to south, respectively). $\delta^{13}C$ values of bulk organic matter from the same samples were more negative, but showed the same general trend ($-14{\cdot}1$, $-13{\cdot}2$, $-12{\cdot}9$, and $-13{\cdot}6$‰ from north to south, respectively)[1]. Therefore, assuming that other CAM plants behave similarily, it is unlikely that isotopic differences in CAM species with latitude are responsible for variations in the $\delta^{13}C$ value of bulk soil organic matter. Instead, it is likely that the isotopic trend from north to south is mainly due to increases in the total biomass of CAM species and additionally to the presence of C_4 grasses at the southernmost site.

The $\delta^{13}C$ values of soil carbonate are determined by the $\delta^{13}C$ value of soil CO_2 at the depth the carbonate forms (Cerling, 1984). The $\delta^{13}C$ value of CO_2 at any depth is a function of the $\delta^{13}C$ value of the decomposing organic matter or respiring roots and the rate of CO_2 production (Cerling *et al.*, 1991). There was little difference in the mean $\delta^{13}C$ values of the pedogenic carbonate of the four sites (Table 4), even though a difference in

Table 4. *The carbon isotopic composition of pedogenic carbonate at the study sites*

Site	Latitude	Soil depth (cm)	$\delta^{13}C$ value (‰ PDB)	Soil PCO_2* (atm)
El Progreso	30°N	6–26	−2·8 (2)†	—‡
		26–46	−4·8 (2)	—‡
		46–66	−4·9 (2)	0·0020
		66–86	−5·9 (1)	0·0039
		86–106	−5·9 (1)	0·0039
		106–126	−6·4 (2)	0·0078
Punta Prieta	29°N	3–23	−1·4 (1)	—‡
		23–43	−2·6 (2)	—‡
		43–63	−4·1 (2)	0·0023
		63–83	−5·2 (2)	0·0086
		83–103	−4·8 (1)	0·0043
		103–123	−5·2 (1)	0·0086
El Arco	28°N	49–69	−5·0 (2)	0·0016
		69–89	−5·2 (2)	0·0018
		89–109	−6·2 (2)	0·0038
		109–129	−6·1 (2)	0·0035
		129–149	−6·6 (2)	0·0069
San Ignacio	27·50°N	55–75	−7·0 (2)	—§
		75–95	−4·9 (2)	0·0059
		95–115	−5·0 (2)	0·0074
		115–135	−4·2 (2)	0·0025

* Calculated from carbonate $\delta^{13}C$ values using model of Cerling *et al.* (1991).
† Isotope value is mean of number of samples (indicated in parentheses) analysed.
‡ CO_2 partial pressure not calculated because sample is within 50 cm of soil surface and isotopic composition likely to be affected by atmospheric CO_2 (Cerling, 1984).
§ Carbonate $\delta^{13}C$ value more negative than value in equilibrium with CO_2 from soil organic matter, thereby giving infinitely high PCO_2 values. May reflect a local C_3-rich organic matter source.

[1]To further test the climatic sensitivity of CAM plant δ^{13} values, we measured the isotopic composition of cellulose from *Yucca schidigera* at four sites along an elevation transect in the Mojave Desert of Nevada (840, 1400, 1750, and 2150 m) (*see* Amundson *et al.* (1989*b*) for further details of study area). The climate along this transect varies significantly (MAT 17·9 to 9·0°C and MAP 160 to 549 mm, from low to high elevation, respectively). The $\delta^{13}C$ values of cellulose showed no notable variation with elevation ($-12{\cdot}4$, $-11{\cdot}1$, $-11{\cdot}9$, and $-11{\cdot}9$‰, from low to high elevation, respectively).

the $\delta^{13}C$ values of organic matter existed. Cerling *et al.* (1991) showed that there is a linear relationship between the $\delta^{13}C$ value of soil CO_2 and CO_2 partial pressure expressed as $1/PCO_2$ (Cerling *et al.*, 1991). The end members of this mixing curve are atmospheric CO_2 (−6‰, pre-industrial values) and the $\delta^{13}C$ value of biologically derived CO_2 (~$\delta^{13}C$ value of soil organic matter plus a 4·4‰ diffusional effect). Therefore, since soil carbonate forms in isotopic equilibrium with soil CO_2, the position that the $\delta^{13}C$ value of carbonate plots on a $\delta^{13}C$ *vs.* $1/PCO_2$ graph for a given soil reveals the approximate PCO_2 at which the carbonate formed, and the biological productivity of the site (since PCO_2 is proportional to soil respiration rates).

The $\delta^{13}C$ values of the carbonate, below 50 cm in depth (i.e. below the depth where atmospheric CO_2 commonly influences that of the soil), of the four soils were plotted on mixing lines appropriate for each profile. The PCO_2 at which each carbonate formed was calculated from the curve for that particular soil. The results are tabulated in Table 4. The carbonates in all soils formed at about the same PCO_2, with the southernmost site reflecting slightly higher pressures. These higher CO_2 pressures correspond to the higher organic matter content of this site, which is an important substrate for microbial production of CO_2. The calculated soil CO_2 partial pressures for all four soils are comparable to those reported for other arid regions (Amundson & Davidson, 1989): slightly greater than Mojave desert soils (~0·001 atm), but similar to measured values in the Sonoran desert of Arizona (~0·003 atm).

The $\delta^{18}O$ values of pedogenic carbonate are determined by (1) the $\delta^{18}O$ values of soil water (Cerling, 1984; Amundson *et al.*, 1989*a*; Quade *et al.*, 1989) and, therefore, precipitation $\delta^{18}O$ values (in the absence of evaporation) and (2) the temperature at which equilibrium between carbonate and soil water occurs (McCrea, 1950). The $\delta^{18}O$ value of precipitation at any location is determined by the complex interaction of a number of factors and processes (Lawrence & White, 1991). There is a phenomenological relationship between mean annual temperature and precipitation $\delta^{18}O$ values for mid to northern latitudes (Dansgaard, 1964; Rozanski *et al.*, 1992) while in tropical regions, the isotopic composition is related to amount of precipitation (Lawrence & White, 1991). Ultimately, the isotopic composition of precipitation at a given location may involve factors such as relative humidity, storm paths, and seasonality (Friedman *et al.*, 1964; Gat, 1980).

Evaporation of soil water enriches the remaining soil water in ^{18}O. For arid soils exposed to long-term evaporation, the $\delta^{18}O$ values of soil water have been shown, both theoretically and empirically, to decrease exponentially with increasing soil depth (Barnes & Allison, 1988). This is also reflected in the soil carbonate which forms in equilibrium with the remaining water (Amundson & Lund, 1987). The evaporative concentration of ^{18}O is most pronounced in the upper 50 cm of the soil, but may extend to greater depths (Barnes & Allison, 1988). In contrast, the transpirational loss of water is usually considered to be a non-fractionating process (i.e. no effect on the isotopic composition of remaining soil water). Therefore, in arid soils with only partial vegetative cover, soil water is ultimately lost through some combination of both evaporation and transpiration and a modification of the isotopic composition of incoming precipitation is to be expected at least in the upper portion of the soil profile.

There are no measured $\delta^{18}O$ values for long-term precipitation in Baja California. From analyses made by Lawrence & White (1991), Baja California lies within a region in which there is a negative relationship between the amount of monthly rainfall and its isotopic composition. Based on global precipitation monitoring, the IAEA (1981) has shown that for most locations, the weighted mean $\delta^{18}O$ value of precipitation can be predicted (as a first approximation) from mean annual temperature, precipitation amount, and latitude. The predicted $\delta^{18}O$ values of precipitation for the study sites are given in Table 5, and the calculations indicate an increase in $\delta^{18}O$ values of precipitation with decreasing latitude. These calculations are supported by isotopic analyses of precipitation on the western coast of the United States (~−8 to −10‰ in Seattle, ~−5‰ near San Francisco; calculated

Table 5. *Calculated $\delta^{18}O$ value of water in equilibrium with pedogenic carbonate at study sites. Carbonate values used in calculations are means for soil profile*

	$\delta^{18}O$ value (‰)			
Site	Carbonate (PDB)*	Water† (SMOW)	Water‡ (SMOW)	Precipitation§ (SMOW)
El Progreso	−3·6	−2·6	−3·6	−5·4
Punta Prieta	−5·2	−4·1	−4·9	−5·1
El Arco	−5·4	−4·1	−3·0	−4·7
San Ignacio	−7·3	−6·2	−5·1	−5·2

* Isotopic standard.
† Calculated using MAT.
‡ Calculated using winter (Nov–Mar) temperatures (for El Progreso and Punta Prieta) or summer (Jul–Sep) temperatures (for El Arco and San Ignacio).
§ Calculated using regression equation from IAEA (1981):

$$\delta^{18}O = [(-16{\cdot}74) + (0{\cdot}483)(T) + (0{\cdot}0005)(P) + (0{\cdot}080)(L)] \pm 2{\cdot}8‰$$

where T = mean annual temperature (°C), P = mean annual precipitation (mm). and L = latitude (degrees).

from precipitation δD values in Friedman *et al.*, 1964), an area dominated by winter precipitation from Pacific storms.

The mean $\delta^{18}O$ values of the soil carbonates follow a trend opposite to that of the predicted precipitation (which implies a constant storm pattern for all sites), and become significantly more negative with decreasing latitude (Table 6). How much of this pattern is due to differences in the $\delta^{18}O$ values in precipitation, variations in the subsequent evaporation of soil water, and to different temperatures at which the carbonates form? If mean annual temperature is used to calculate the isotopic composition of the precipitation that the carbonates formed from, the resulting $\delta^{18}O$ values of soil water parallel that of the carbonate (− 2·6 to 6·2‰, north to south) (Table 5), since all sites have about the same mean annual temperature. However, it is likely that the carbonate in the southern sites form in the late summer or fall (based on their depth and their morphology on soil gravels) and that the northern sites form carbonate mainly in the winter or spring (based on their respective morphology). If mean winter temperatures are used for calculations at the northernmost sites, and summer temperatures for the southern sites, the isotopic differences in calculated precipitation values between the north and south are somewhat diminished (− 3·6 to − 5·1‰, north to south) (Table 5), but are still present. It appears that regardless of the actual temperature at which the soil carbonates form, the $\delta^{18}O$ values of the soil water from which they formed becomes more negative in the south, contrasting with general predictive models.

What factors are responsible for this trend in soil water $\delta^{18}O$ values? Three explanations are possible: (1) similar rainfall $\delta^{18}O$ values at all sites that are modified by subsequent evaporation, (2) decreasing $\delta^{18}O$ values of precipitation as the proportion of summer and fall rainfall increases, or (3) some combination of 1 and 2. In the northern two sites (which have carbonate present almost to the soil surface), there is an apparent trend of decreasing carbonate $\delta^{18}O$ values with depth, probably reflecting evaporative effects on soil water near the soil surface (Table 6). The $\delta^{18}O$ values of soil carbonate at greater depths may also reflect some evaporative loss, although this would be true for all four soils since they all have similar amounts of vegetative cover and, as a first approximation, proportions of evaporative *vs.* transpirational water loss. Therefore, it is likely that the $\delta^{18}O$ values of the soil carbonates at depths below 50 cm may reflect differences in the isotopic composition of

Table 6. *The oxygen isotopic composition of pedogenic carbonate at the study sites*

Site	Latitude	*Soil depth* (cm)	$\delta^{18}O$ value (‰ PDB)
El Progreso	30°N	6–26	−2·6 (2)*
		26–46	−3·5 (2)
		46–66	−3·9 (2)
		66–86	−3·0 (1)
		86–106	−3·7 (1)
		106–126	−4·3 (2)
Punta Prieta	29°N	3–23	−3·7 (1)
		43–63	−5·2 (2)
		63–83	−5·9 (2)
		83–103	−5·7 (1)
		103–123	−5·1 (2)
El Arco	28°N	49–69	−4·9 (2)
		69–89	−4·9 (2)
		89–109	−5·0 (2)
		109–129	−5·9 (2)
		129–149	−6·1 (2)
San Ignacio	27·50°N	55–75	−8·5 (2)
		75–95	−7·0 (2)
		95–115	−7·0 (2)
		115–135	−6·5 (2)

* Isotope value is mean of number of samples (indicated in parentheses) analysed.

rainfall between the sites. As discussed earlier, sites which receive large proportions of their total precipitation in short time spans generally have more negative $\delta^{18}O$ values than sites which receive more evenly distributed precipitation (the amount effect) (Lawrence & White, 1991). A comparison of the percentage of total rainfall that falls each month between the northern and southernmost sites in this study (Fig. 3) emphasizes the

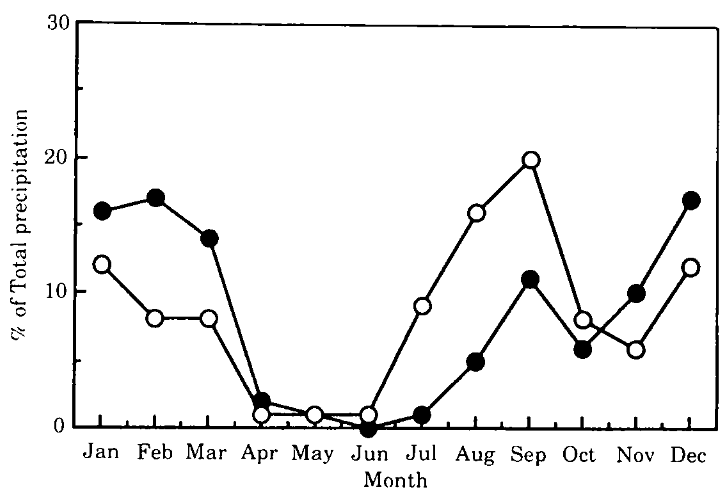

Figure 3. The percentage of total precipitation received on a monthly basis at El Progreso (–●–) (30°N) and San Ignacio (–○–) (27·5°N).

differences between these two portions of the Vizcaíno Desert and shows how rain is more concentrated in a shorter time span in the south. This figure, based on long-term averages, fails to illustrate the more sporadic nature of summer tropical storms and the greater year to year variations in total amounts that occur in areas subject to these tropical disturbances (Hastings & Turner, 1965). Therefore, the mean values illustrated can greatly underestimate the totals that may fall in given years. Therefore, from these arguments, it may be hypothesized that summer and early fall precipitation in the Baja California peninsula is isotopically more negative than that from the more gentle, and evenly distributed, winter storms. In the absence of long-term precipitation monitoring in the region, this hypothesis could be tested further by isotopically analysing soil carbonate from sites further to the south, which receive even greater proportions of summer and fall precipitation (CISESE, 1990).

Discussion

The floral distribution of Baja California is undoubtedly a temporal feature, responding to the whims of climate change. Climatic reconstructions for the glacial maximum of the latest Pleistocene suggest stronger winter storm patterns, and weaker summer monsoons, for the Baja California Peninsula (e.g. Spaulding & Graumlich, 1986). The refinement of past floral and climatic patterns, for what is today the Vizcaíno desert, will rely on a variety of sources, including paleosols and fossil plants. In our initial investigation of the area, we observed that paleosols, or 'relict soils' (soils exposed to multiple soil-forming intervals), are present on higher stream terraces. The isotopic composition of these or other paleosols can provide valuable insights into past conditions, particularly if interpreted in light of the contemporary climate and the corresponding soil isotopic composition. The results of the work presented here provide baseline information on the present-day climate/soil isotope relationships, and are relevant to future paleoclimate studies in the following ways: (1) The positioning of carbonate coatings on soil gravels (Amundson *et al.*, 1992) appears sensitive to winter *vs.* summer dominated rainfall; (2) The oxygen isotope composition of pedogenic carbonate varies considerably over a short distance and appears to be sensitive to present storm patterns. Based on our data, we predict that increases in winter rainfall should result in more positive $\delta^{18}O$ values and that increases in summer rainfall would cause an opposite effect (assuming no significant change in temperature patterns); (3) The carbon isotope composition of soil organic carbon (a component unlikely to be preserved in relict soils) varies slightly with the present rain distribution. Based on our limited data, and on other work (Terri & Stowe, 1976), a decrease in the summer rainfall quantities should decrease both CAM biomass and C_4 grasses, leading to a decrease in the $\delta^{13}C$ value of the soil organic matter and soil carbonate (Cerling *et al.*, 1989); and (4) The carbon isotope composition of CAM plants measured in this study cast some doubt on the sensitivity of their $\delta^{13}C$ values to the climate variations expected from pluvial to inter-pluvial times.

This study reveals the degree to which the flora of the Vizcaíno desert has adapted to different patterns of precipitation. Additionally, the study shows the sensitivity of stable isotopes in the soil environment to the differences in plant and rainfall distribution. However, as our discussion of the oxygen isotope variations revealed, there is much to be learned about the present rainfall/isotope relationship in this region. The measured variations in plants and stable isotopes are just part of a larger pattern that exists in the Baja California peninsula. Future isotopic work in other floral provinces should reveal more about the Holocene distributions of rainfall and vegetation in this unique portion of North America, ultimately serving as basis for detailed explorations of paleoclimatic oscillations in this region.

Financial support for this work was provided by the UCR/Mexico Collaborative Research Program, the University of California Experiment Station Hatch Funds, and a grant from the National Science

Foundation (NSF ATM 91-21289). We thank Dr M. Conrad and Mr D. Schrag for assistance with mass spectrometry. Alicia Gonzalez-Ramirez helped identify plants. Dr Yang Wang provided comments on an earlier version of this paper.

References

Amundson, R. G. & Lund, L. J. (1987). The stable isotope chemistry of a native and irrigated Typic Natrargid in the San Joaquin Valley of California. *Soil Science Society of America Journal*, **51**: 761–767.

Amundson, R., Graham, R. C., Franco-Vizcaíno, E. & DeNiro, M. J. (1992). The effect of seasonality of precipitation on the chemistry and morphology of carbonate in soils of Baja California, Mexico. *297, Agronomy Abstracts*. Madison, WI: American Society of Agronomy.

Amundson, T. G., Chadwick, O. A., Sowers, J. M. & Doner, H. E. (1989*a*). The stable isotope chemistry of pedogenic carbonates at Kyle Canyon Nevada. *Soil Science Society of America Journal*, 53: 201–210.

Amundson, R. G., Chadwick, O. A. & Sowers, J. M. (1989*b*). A comparison of soil climate and biological activity along an elevation gradient in the eastern Mojave desert. *Oecologia*, **80**: 395–400.

Amundson, R. G. & Davidson, E. A. (1990). Carbon dioxide and nitrogenous gases in the soil atmosphere. *Journal of Geochemical Exploration*, **38**: 13–41.

Barnes, C. J. & Allison, G. B. (1988). Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *Journal of Hydrology*, **100**: 143–176.

Cerling, T. E. (1984). The stable isotope composition of modern soil carbonate and its relationship to climate. *Earth and Planetary Science Letters*, **71**: 229–240.

Cerling, T. E., Quade, J., Wang, Y. & Bowman, J. R. (1989). Carbon isotopes in soils and paleosols as ecology and paleoecology indicators. *Nature*, **341**: 138–139.

Cerling, T. E., Solomon, D. K., Quade, J. & Bowman, J. R. (1991). On the isotopic composition of soil carbon dioxide. *Geochimica et Cosmochimica Acta*, 55: 3403–3405.

CICESE (1990). Estudios del balance de agua. In: Coa, S. R., Reyes, F. M. & López, J. G. (Eds), *Climatología del la Región Noroeste de México*. Ensenada, BC, Mexico: Grupo de meteorología Centro de investigación científica y de educación superior de Ensenada.

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, **16**: 436–468.

Deines, P. (1980). The isotopic composition of reduced organic carbon. In: Fritz, P. & Fontes, J. Ch. (Eds), *Handbook of Environmental Isotope Geochemistry. Vol. 1. The Terrestrial Environment*, pp. 329–406. New York: A. Elsevier. 545 pp.

Friedman, I., Redfield, A. C., Schoen, B. & Harris, J. (1964). The variation of the deuterium content of natural waters in the hydrologic cycle. *Reviews of Geophysics*, 2: 175–224.

Gat, J. R. (1980). The isotopes of hydrogen and oxygen in precipitation. In: Fritz, P. & Fontes, J. Ch. (Eds), *Handbook of Environmental Isotope Geochemistry. Vol. 1. The Terrestrial Environment*, pp. 21–47. New York: A. Elsevier. 545 pp.

Hastings, J. R. & Turner, R. M. (1965). Seasonal precipitation regimes in Baja California, Mexico. *Geografiska Annaler*, **47A**: 203–223.

IAEA (International Atomic Energy Agency) (1981). Statistical treatment of environmental isotope data in precipitation. International Atomic Energy Agency Technical Report Series 206.

Lawrence, J. R. & White, J. W. C. (1991). The elusive climate signal in the isotopic composition of precipitation. In: Taylor, Jr., H. P., O'Neil, J. R. & Kaplan, I. R. (Eds), *Stable Isotope Geochemistry: A Tribute to Samuel Epstein*. Special Publication No. 3, pp. 169–185. Trinity University, San Antonio, TX: The Geochemical Society, Divison of Science, Mathematics, and Engineering. 516 pp.

McAuliffe, J. R. (1991). Demographic shifts and plant succession along a late Holocene soil chronosequence in the Sonoran Desert of Baja California. *Journal of Arid Environments*, **20**: 165–178.

McCrea, J. M. (1950). On the isotope chemistry of carbonates and a paleotemperature scale. *Journal of Chemical Physics*, **18**: 849–857.

Minagawa, M., Winter, D. A. & Kaplan, I. R. (1984). Comparison of Kjeldahl and combustion methods for measurement of nitrogen isotope ratios in organic matter. *Analytical Chemistry*, **56**: 1859–1861.

Osmond, C. B., Allaway, W. G., Sutton, B. G., Troughton, J. H., Queiroz, O., Luttge, U. & Winter, K. (1973). Carbon isotope discrimination in photosynthesis of CAM plants. *Nature,* **246**: 41–42.

Quade, J., Cerling, T. E. & Bowman, J. R. (1989). Systematic variations in carbon and oxygen isotopic composition of pedogenic carbonate along elevational transects in the southern Great Basin, United States. *Geological Society of America Bulletin,* **101**: 464–475.

Rozanski, K., Araguas-Araguas, L. & Gonfiantini, R. (1992). Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate. *Science,* **258**: 981–985.

Soil Survey Staff (1981). Examination and description of soils in the field. USDA-SCS Soil Survey Manual, Issue 1. Washington, DC: US Government Printing Office.

Spaulding, W. G. & Graumlich, L. J. (1986). The last pluvial climatic episodes in the deserts of southwestern North America. *Nature,* **320**: 441–444.

Sternberg, L. S. L. (1989). Oxygen and hydrogen isotope measurements in plant cellulose analysis. In: Linskens, H. F. & Jackson, J. F. (Eds), *Modern Methods of Plant Analysis, Vol. 10. Plant Fibers*, pp. 89–99. Springer-Verlag. 377 pp.

Teeri, J. A. & Stowe, L. G. (1976). Climatic patterns and the distribution of C_4 grasses in North America. *Oecologia,* **23**: 1–12.

Wiggins, I. L. (1960). The origins and relationships of the land flora. In: *The Biogeography of Baja California and Adjacent Seas*, Part III. Terrestrial and fresh-water biotas. *Systematic Zoology,* **9**: 148–165.